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The role of fringing coral reef in beach protection of Hurghada, Gulf of Suez, Red Sea of Egypt

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Abstract

The coral-reef system fronting most of the coastline of the Red Sea provides natural protection to the aquatic system. Its pronounced morphologic features protect coastal recreation facilities located behind the reef. To provide a basis for evaluating the role of the fringing coral reef in protecting marinas and sandy beaches against waves and currents, a two-dimensional (2D) numerical model "SIMulating COastal PROcess" (SIMCOPRO) was applied with its three main modules including wave, current and sediment. The selected study area is located at Sahl Hasheesh coast south of Hurghada on the west coast of the Red Sea at a site proposed for the construction of a marina. The model offers insight in how the reef system modifies the wave and current fields. The application of the model in the presence of a marina reveals insignificant erosion on the downdrift side of the marina breakwaters (south of the southern breakwater). The erosion is expected to be 1 m after the first year, 2 m after the next 5 years and no further change for a period of 10 years. This is because the rocky reefal beachface will be exposed and erosion of sand will be diminished. The minor local erosion is controlled by the protective response of coral reef, the very limited coarse sand on the beachface (<0.5 m thick), the weak current induced by waves (0.13 m/s) and other topographic protective elements in the region. The submerged/emerged geometric nature of the reefal system, both reef flat and reef crest, allow wave dissipation and thus behaves as a submerged breakwater to protect marinas or artificial beaches in the shelter zone of this reef. An important lesson to be learned from this study is that improper construction practices of building marinas can seriously hurt the environment. The dredging of artificial reef lagoons is one improper practice that would create unexpected beach erosion.

Keywords: Red Sea; Suez gulf; Coral reef; Beach protection; Artificial lagoons; Recreation facilities; Mathematical model

1. Introduction

Most of the Red Sea shoreline is fronted by a discontinuous series of extensive fringed coral reefs. In some areas such as Hurghada these reefs are fronted by a group of barrier islands made up of igneous and metamorphic rocks (Fig. 1A). Geomorphologically, the shoreline of the Red Sea varies in shape and composition. It varies from rocky to sandy, with low or high relief topography of cliffs and headlands. The sand beaches are limited in thickness (<1 m overlays

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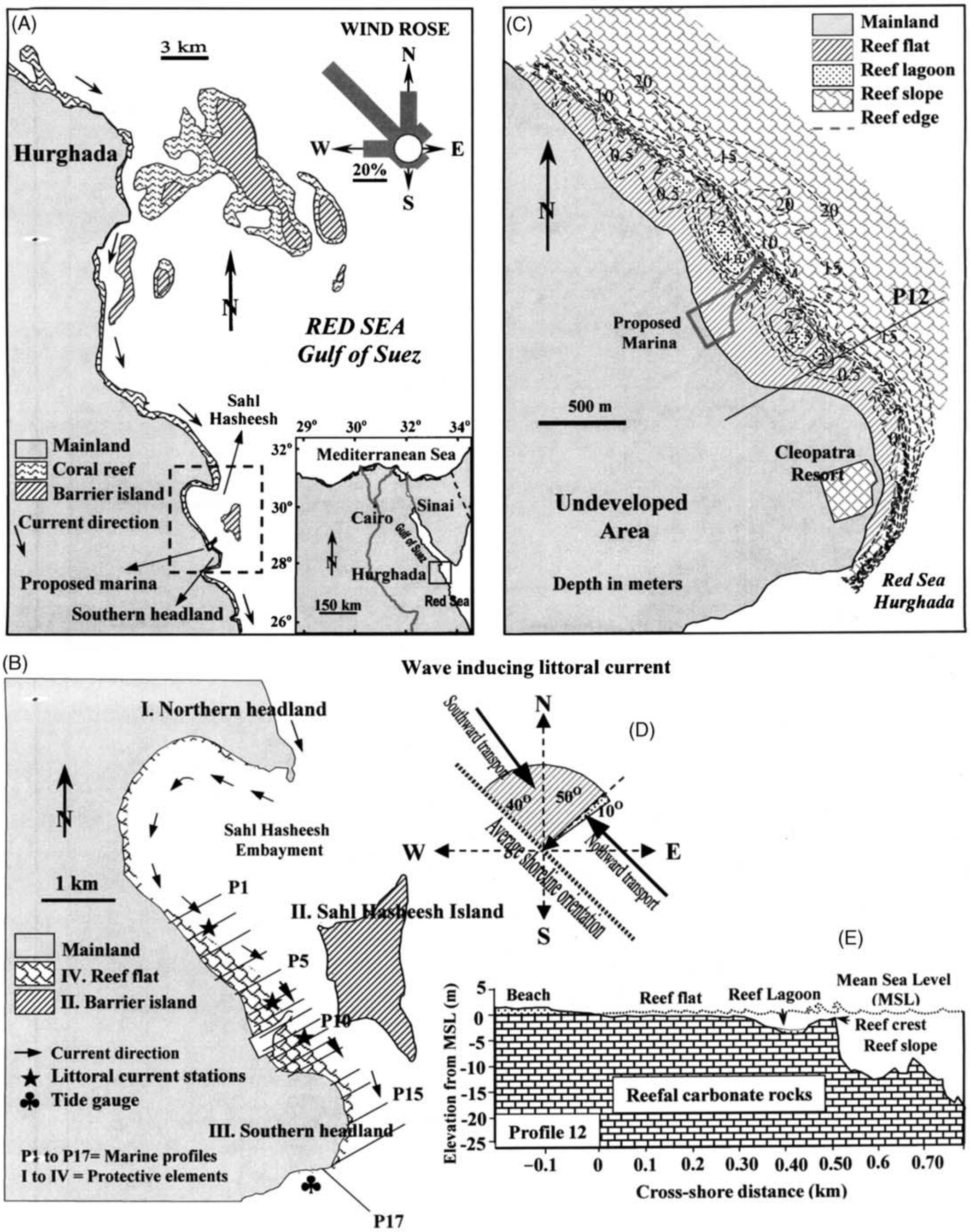

Fig. 1. Maps of Hurghada, Gulf of Suez, Red Sea showing: (A) study area at Sahl Hasheesh embayment and the location of proposed marina; (B) field activities and the natural protective system; (C) bathymetric features surveyed in August 2002 depicting main features of the reef; (D) effective waves-inducing littoral current versus average shore orientation; (E) selected cross-shore profile (P12) depicting seabed topographic features across the reef system. The surface of this reef, with its high relief and varied topography, causes the waves to break and thus protecting adjacent beaches.

the reefal rocks). The main sources of sediments to the beaches of the Egyptian Red Sea are terrestrial deposits transported from the fringing mountains during the occasional runoffs through the numerous wadis to the sea (Said, 1962). Mostly, the shoreline is backed by a wide coastal plain followed by rocky mountains consisting mostly of crystalline rocks belonging to the Eastern Desert or to Sinai Peninsula (Fig. 1A).

The tide of the Red Sea is semi-diurnal with gradually decreasing magnitude from two meters near the city of Suez to the nodal zero point at the city of El-Tor, some 210 km to the south (Nir, 1996). Winds mainly blow from the NW and N during most of the year, whereas it blows from the south and southeast during the monsoon "Azyab" storms (Fig. 1A) (RSGAP, 1980; CRI, 1994). Generally, currents along the Gulf of Suez shores are predominantly weak and their direction is towards the south (Fig. 1A). Currents in the Red Sea are induced by tidal current, wind driven current, currents generated by wave breaking on shoals and littoral current generated by wave breaking close to the shoreline (in areas without reef flat).

The rapid and uncontrolled development of the Red Sea coast has resulted in a series of disturbances that are not friendly with the surrounding environment. These developments involve excavations for creating artificial lagoon used as swimming pools and marinas. Large amount of fillings on the reef flat are dumped to create space and solid embankments are built as jetties and mooring areas. Subsequently, the living corals in the reef system have suffered dramatic and irreversible degradation. In addition, the depositional-hydrodynamic patterns have been altered as a result of blocking littoral currents by protruded constructions. Examples of these infringements along the water front of Hurghada have been discussed by Frihy et al. (1996), CRI (1994), El Gamily et al. (2001), Moufaddal (2001), Dewidar (2002).

A pilot area was selected at Sahl Hasheesh embayment about 20 km south of Hurghada on the west coast of the Red Sea (Fig. 1A). The shoreline is a narrow beach bare or covered with sand. The beach is backed by a plain broad backshore occasionally covered with small primitive dunes. The surrounding coastline and its contiguous coastal plain are totally undeveloped. The pilot area was selected to implement a central marina to meet the demand for the new recreation development in the region (12 km of coastline) (Fig. 1B). The objective of this study is to evaluate the importance of the fringing reef in protecting the coastal area against waves and currents. The defensive response of reef against coastal processes is assessed mathematically. The mathematical model predicts possible changes in the shoreline positions as function of main coastal processes, waves and currents.

2. Methods

2.1. Field survey

A total of 17 marine hydrographic profiles were surveyed along the shore of the study area. Seabed composition is identified (soft sediment or rocks) (Fig 1C). Profile lines were spaced 150 and 300 m apart and are nearly perpendicular to the coastline covering the beach to the reef slope (Fig. 1B). They extend to about 1000 m offshore to a maximum water depth of 65 m. The leveling of the beachface and the sounding of the shallow water <0.5 m across the tidal flat was surveyed on foot using conventional leveling instruments together with the GPS at about 10 m interval. The deeper tidal slope part fronting the tidal crest was surveyed using a boat equipped with a digital Echo Sounder "model JRC FF10" and a GPS "model Map 330" (with a relative accuracy of <1 m and horizontal accuracy of ± 5 m), both were attached with a Laptop computer. Surveying of the beachface was determined using leveling instruments and the GPS. Soundings were corrected to the low water level relative to a known geodetic benchmark at the backshore. The water level is read every 15 min using a graded stave fixed in a proper area down coast of the southern headland (Fig. 1B). Longshore current measurements were taken during the field work at three stations (Fig. 1B). Current measurements were obtained between the outer part of the tidal flat and the reef crest by following the movement of a buoy and measuring the time it takes to travel a distance of 30 m in the longshore direction. At each profile line sediment samples were obtained from the upper beachface marking the high water level (16 samples). In some localities, however, beach rocks, exposed on the surface with no sand, e.g., at the down drift of the marina site (Fig. 1B). In addition, nine sediment samples were obtained from the thin layer of the tidal flat by a small grab sampler.

Sediment samples were sieved for 15 min with a Ro Tap shaker using standard (USA) at whole phi interval. The mean grain size (Mz) for each sample was calculated using the formula of Folk and Ward (1957).

2.2. Modeling

We applied both the one-dimensional (1D) and two-dimensional (2D) models. The 2D model is applied because the sediments covering the beachface of the study area are sparse in thickness and spatial distribution. In some areas there is no sediment, only the basement reefal rocks. The 1D model is used to predict the behavior of the fringing reef in beach protection and shoreline changes. The 1D model assumes that sand layers covering the reefal rocks exist at infinity, i.e., unlimited sand. By comparing and contrasting the outputs of the two models, the role of the coral reef in beach conserving sediments is revealed.

2.2.1. Two-dimensional model (2D)

A 2D mathematical model "SIMulating COastal PROcess" (SIMCOPRO) has been developed with its three main modules including wave, current and sediment (El Sayed, 2004). The model was applied to simulate the coastal processes in the study area in two situations, prior to constructing the proposed marina breakwaters and after construction of this marina. The output results of this model provide information pertaining to coastal processes including wave characteristics, wave distribution, current distribution and the contour bed changes. Details of this model are cited in (El Sayed, 2004). The wave module includes wave characteristics: wave height (H), wave length (L), wave direction (θ) and wave period (T), at each node of the grid.

The main equations used in this module are (Dalrymple, 1988):

$$\frac{\partial(K\sin\theta)}{\partial x}=\frac{\partial(K\cos\theta)}{\partial y}$$

and

$$\frac{\partial(EC_g\cos\theta/\sigma)}{\partial x}=\frac{\partial(EC_g\sin\theta/\sigma)}{\partial y}$$

where K is the wave number, θ the wave angle, x the on-offshore distance, y the longshore distance, E the wave energy, σ the wave frequency, and C_g is the wave group celerity. The wave diffraction is calculated by using the method of Goda (1985). The general continuity and motion equations used in this model are given by Horikawa (1978). The topographical changes are determined from the continuity equation (Shore Protection Manual, 1984) given by

$$\frac{\partial d}{\partial t}+\left[\frac{1}{1-\lambda}\right]\left[\left(\frac{\partial q_x}{\partial x}\right)+\left(\frac{\partial q_y}{\partial y}\right)\right]=0.0$$

where λ is the bottom sediment porosity, d the water depth and (q_x) and (q_y) is the sediment transport in the two direction. The wave characteristics are predicted by using automated coastal engineering system (ACES) prepared by US Army Corps of Engineers, Washington, 1992. The Input data are the recent surveyed contour map commenced in August 2002, the sediment characteristics (mean grain size in mm) and the wave characteristics (wave height, period and direction). Waves are monthly predicted from the monthly wind data measured at Hurghada.

2.2.2. One-dimensional model (1D)

We used the well known 1D GENESIS shoreline modeling system (SMS) model developed by the COE USA (Gravens et al., 1991) to simulate shoreline changes after 1–3 years. By applying this model we assume that the study area is entirely composed of beach sand with no reef rocks. The wave characteristics calculated by using Snell's law assuming parallel contour lines. The shoreline surveyed in August 2002 is used within a fine grid cell ($D_x = 90$ m) to run the model. The monthly waves are calculated from the wind data resulted from applying the ACES model. Mean grain size D_{50} is also used.

3. Results and discussion

3.1. Beach-seabed configuration

Data obtained from the 17 marine profiles and shoreline survey were used to construct the spatial profile configuration (distance from baseline versus leveling and sounding of each profile line) and to construct a computer-generated contour map (Fig. 1C and E). Results of the field survey indicate that the intertidal zone (tidal flat) is less than 100 m in the northern part of Sahl Hasheesh and increasing in width southward where the proposed marina is located (∼500 m) and decreases again further south (∼100 m) down coast of the southern headland. The reef edge separates the tidal flat from the tidal slope. It has been noticed that the tidal flat area is occasionally exposed during low tide and partially/totally submerged at high tide (Fig. 1C and E). Emerged large boulders are scattered allover the tidal flat area. Profile line 12 is selected from the study profiles to generalize the seabed configuration of the study area (Fig. 1E). This configuration is typical for the classical coastal topography along most of the Red Sea coast. The topology is fronted by fringing reef composed of coastal plain, reef flat, reef crest, reef edge and reef slope. The reef flat has a low-diversity corals and coralline algae associated with natural lagoons and fore-reef, it is followed seaward by the reef crest and reef edge (Fig. 1E). The reef edge is followed by a steep drop-off that characterizes the reef slope. The reef slope has extensive coral-reef production. Because of the unawareness of the importance and delicacy of the Red Sea ecosystems, resort developments often incorporate improper designs of recreation facilities. Most serious is the illegal dredging used to create artificial lagoons or earth embankment landfill to implement mooring jetty.

Field observations indicated that the beachface and its contiguous intertidal flat zone and subtidal zone are partially covered with detrital sand (<5 cm thickness). They formerly had a rocky surface composed of coral reef (relict and living). Further shoreward, the inner part of the reef flat is partially covered with a relatively thin layer of fine-grained sediments (average mean grain size = 0.24 mm; range of 0.20–0.32 mm). Sand partially covers the beach and the inner shallow part of the tidal flat, about half of its width. The outer part of the tidal flat and its contiguous tidal slope including the tidal crest is mainly composed of reefal rocks (Fig. 1E). Sand also covers the bottom of the natural lagoons "pools" which exist on the outer part of the tidal flat (Fig. 1C and E). Coarse-grained sand covers the beach (average mean grain size = 0.68 mm; range of 0.53–0.87 mm) and its contiguous backshore of the study area. The sand beach is decreasing in thickness southward along the length of the coastline and partially diminished nearby the proposed marina site. An interesting question arises: why the coarse-grained beach sediment derived from the northern part of Sahl Hasheesh embayment has not had time to move further to the south, so that it is found along the entire length of the littoral cell of the study area. Our interpretation is that the littoral current prevailing in the area is too weak to disperse this sand toward the southern part of the study area. This current is induced from the processes of waves dissipating across the broad reef flat surface which functions as a submerged breakwater along the length of Sahl Hasheesh embayment.

3.2. Applying the 2D model

The coastline of Hurghada is naturally sheltered against waves dominantly blown from the N (09°) and NW (315°) quadrant whereas it is exposed to the NNE waves. The prevailing waves calculated are small (<1.0 m height) and head the NNE (022°) direction. The prevailing waves approaching the study area before constructing the marina breakwaters are toward the NE direction across the reef slope with a maximum wave height of 2 m (Fig. 2A). Starting from the reef edge, waves reverted to be perpendicular to the shore and decreasing in height due to the sudden shoaling of the water depth, being <1 m in height. Waves approaching the reef lagoons show slight increase in their heights. This is due to the diverse changes in water depth between the tidal flat and the local water lagoons. The predicted waves are very small in the middle of the tidal flat and progressively diminish near the shore. The wave distribution off the southern headland shows a convergence pattern. Following construction of the marina breakwaters, the wave distribution is similar to that pattern before the construction (Fig. 2B). The only difference is that the wave heights are reduced in the shadow area south of the southern breakwater of the proposed marina being ∼40 cm in height.

The predicted current distribution in the area prior to construction of the marina tends to be very low with a maximum of 1.6 m/s on the outer part of the tidal flat (seaward side) and completely diminished in the middle part being 0.4 m/s (Fig. 2C). Further seaward along the reef edge, current is directed southeast in the longshore direction with an average of 0.12 m/s. The current simulated after constructing the marina is similar to the general patterns before the construction except near the tip of the breakwaters where current speed getting slightly faster (Fig. 2D).

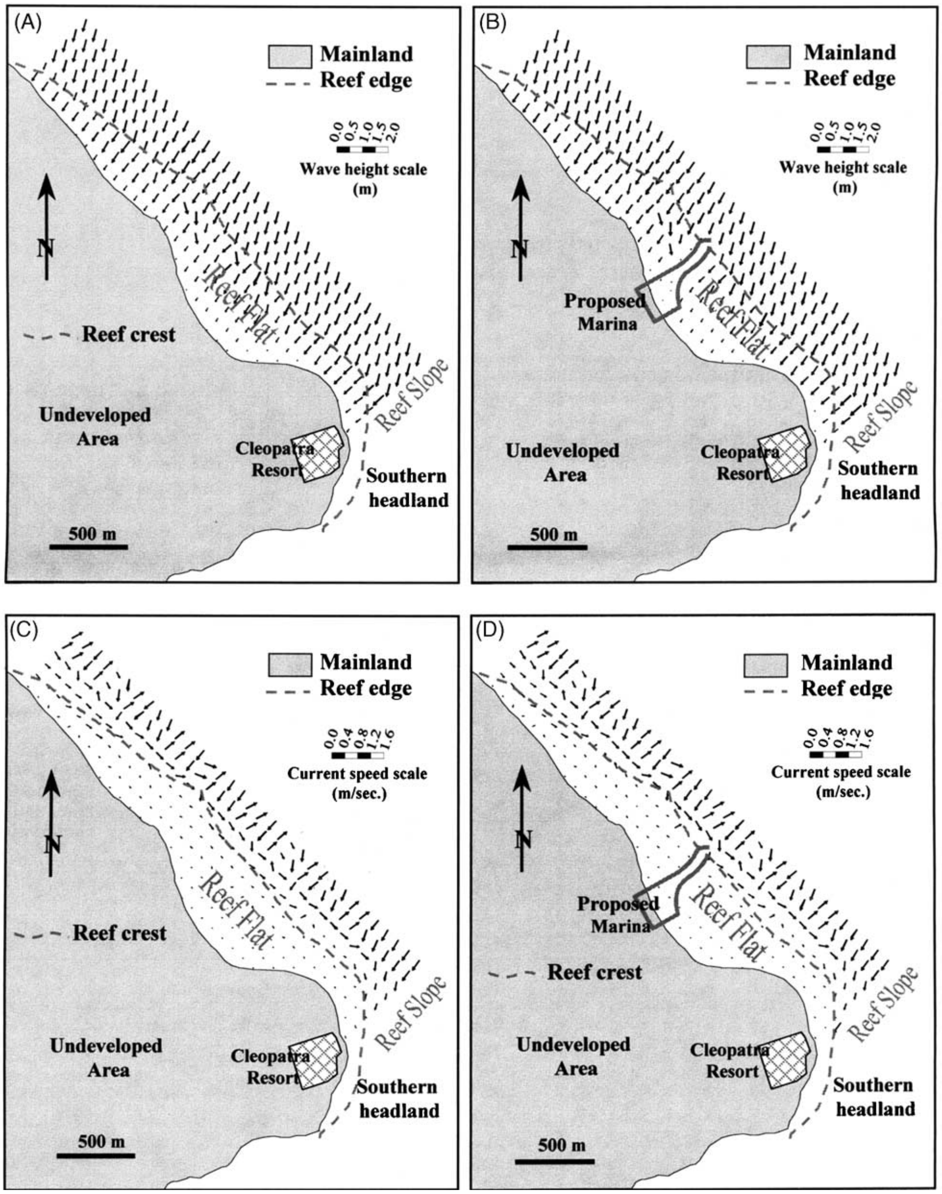

Fig. 2. Coastal processes simulated from applying the 2D mathematical model off the southern part of Sahl Hasheesh prior to and after implementing the proposed marina: (A) and (B) wave pattern; (C) and (D) current pattern. Ho (wave height in deep water) = 0.6 m and T (wave period) = 4.0 s.

Measurements of longshore current speed recorded during the field survey ranges between 0.1 and 0.13 m/s and trending southeast. Longshore current is formed from waves obliquely approaching a coastline at an angle. Longshore current direction is deduced from the relationships between the effective angle of incident waves and average shoreline orientation (Fig. 1D). Analysis of incident waves versus shoreline orientation revealed that the NW, NNW, N, NNE and NE (totaling 90°) waves are jointly acting to generate current toward the southeast (Fig. 3D). Conversely, small wave components approach from

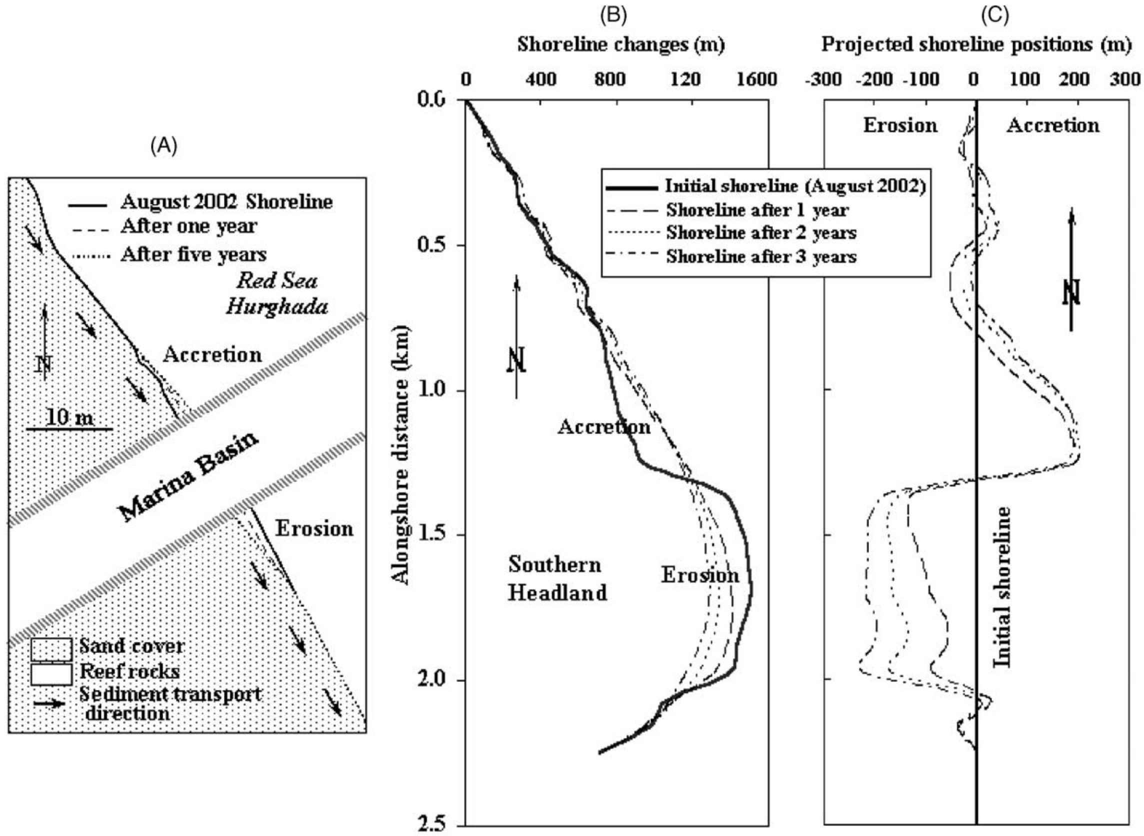

Fig. 3. Shoreline changes predicted from applying two models alongshore of Sahl Hasheesh embayment: (A) minor shoreline changes predicted updrift and downdrift of the marina basin resulted from applying the 2D mathematical model (present condition); (B) and (C) significant beach changes resulted from applying the 1D mathematical (assumed condition). Locations are shown in Fig. 1B.

ENE (10°) are responsible to drive current to the north.

Owing to the rocky nature of the seabed no significant changes have been predicted in the water depth contours applying the 2D model. Shoreline changes predicted, with narrow grad around the marina, depict changes at the downdrift and updrift of the marina basin and extending alongshore up to ∼10 m on both sides of the marina basin (i.e., both to the north and to the south) (Fig. 3A). Shoreline prediction indicates that insignificant erosion would occur at the downdrift side of the marina basin (south of the southern breakwater), amounting to 1 m after the first year following construction of the marina, and 2 m after the next 5 years. No additional changes are expected after 10 years. This erosion is local and extends southward to ∼10 m. Sand covers the beach rocks attaining less than 0.5 m thick. Eroding of such sand after the first 5 years will entirely expose the reefal rock on the beachface. In fact, this rocky beachface will remain exposed with no further changes. The predicted local shoreline erosion will not continue further south due to the sudden deflection in the shoreline orientation forming the southern headland. The protruding nature of this headland will also act as a natural structure to stop sediment bypassing south. This headland represents the southern end of the littoral cell of Sahl Hasheesh and will prevent any traces of sediment to bypass further south. Further north, local accumulation of sand will appear at the updrift side of the marina basin and extending for ∼10 m northward (Fig. 3A). This accretion attains 1 m after the first year following construction of the marina, 2 m after the next 5 years and no further changes would appear after the following 10 years as the source sand feeding this accretion area is limited. Shoreline changes predicted are expected on the coastline position adjacent to the marina breakwaters. The weak hydrodynamic processes prevailing in this protected region explain these insignificant local changes (very limited in space). The northern and southern headlands, the eastern offshore island and reef flat surface are natural features that protect the studied area (Fig. 1B). These natural features assist in dissipating storm waves on the broad tidal flat before reaching the coastline and thus inducing weak currents that have no capability to move sediment covering the reefal rocks. The calculated current speed is too weak 0.04 m/s to transport fine sand on the tidal flat (Mz = 0.24 mm) and the beach sand either (Mz = 0.68 mm). Even though, this current can allow tidal sediments to be in a state of incipient motion.

3.3. Applying the 1D shoreline change model (GENESIS)

The results of applying shoreline changes and projected values are estimated using the model "GENESIS" for the imaginary case of sandy beach without reef flat or rocky area is displayed in Fig. 3B. As expected, significant shoreline erosion occurred at the tip of the northern headland followed by accretion along its northern saddle. Maximum erosion of 138, 174 and 228 m, respectively, is predicted over 1, 2 and 3 years (Fig. 3C). This erosion is corresponding to a maximum accretion of 189, 198 and 190 m along the northern saddle between 0.56 and 1.07 km from the initial point. The accretion/erosion pattern is resulted from the wave-induced northern currents which transport eroded sand from the headland tip towards the south.

Results obtained from applying the two models confirm the protective response of coral reef against waves in turn it can be taken as advantage to implement central marinas or artificial beaches in the shelter zone of this reef. However, appropriate protection measures should be considered during dredging the marina basin and its contiguous navigation channel. The relevant location of the dumping site should be selected further inland to minimize run off.

4. Conclusions

In order to assess the role of coral reef in protecting the coastline 1D and 2D numerical models are applied at Sahl Hasheesh embayment, south of Hurghada on the Red Sea coast of Egypt. The two models demonstrate two conditions. Firstly, dealing with the existing condition in which the sand beach is limited in thickness and overlying the reefal rocks so that the 2D model was applied. Secondly, we assumed that the beach is entirely composed of unlimited sediment with no reefal rocks so we used the 1D GENESIS model. Simulated shoreline changes in the vicinity of the proposed marina is insignificant when applying the 2D model (1 m after the first year and followed by 2 m after the next 5 years and no further changes after 10 years). Assuming that the reef is non existent, dramatic erosion could occur (228 m after 3 years) when applying the 1D model. This substantial difference between the shoreline changes predicted from running both models confirm that the varied topography of the reef system, the reef flat and reef crest in particular, are acting as a natural coastal protection system. Incoming waves break and expend their energy on the reef, thereby sheltering the adjacent coastline. The wave energy is much less at the beach when the reef is present. Reefs act as natural breakwaters and perform the same functions as those described for offshore breakwaters. Acting together with this hydrodynamic response is the very limited sand covering the beach and the protective morphologic features (reef surface, barrier islands and headlands). Results of applying these models confirm that coral reefs are an important recreational and aesthetic resource for tourists and can provide protection for marinas and beaches, which are often found behind reefs. Moreover, conserving this reef is a benefit to protect water front facilities.

Sensitive coral-reef areas should consider the natural protective elements that in turn would minimize dredging to create recreation facilities and thereby not affecting the surrounding environment. Fine grained sediments resulting from dredging activity badly affect the living corals nearby. Such dredging of coral reef also would have a negative effect on the stability of the beach and cause losses and damage for the recreation facilities. Engineers, architects, bankers, and planners contributed in design and building recreation facilities should be fully aware with the high sensitivity of coral-reef ecosystems. Because of poor understanding of this system, most of them would apply traditional measures cited in textbooks such as design artificial lagoons on the reef flat system.

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